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Process effect of microalgal-carbon dioxide fixation and biomass production: A review

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ABSTRACT

Global warming caused by anthropogenic CO_2 emission has been one of the most important issues in the fields of science, environment and even international economics and politics. To control and reduce CO_2 emissions, intensive carbon dioxide capture and storage (CCS) technologies have been comprehensively developed for sequestration of CO_2 especially from combustion flue gas.

Microalgae-based CO_2 biological fixation is regarded as a potential way to not only reduce CO_2 emission but also achieve energy utilization of microalgal biomass. However, in this approach culture process of microalgae plays an important role as it is directly related to the mechanism of microalgal-CO_2 fixation and characteristics of microalgal biomass production. The aim of this work is to present a state-of-the-art review on the process effect, especially on the effects of photobiochemical process, microalgal species, physicochemical process and hydrodynamic process on the performance of microalgal-CO_2 fixation and biomass production. Also, the perspectives are proposed in order to provide a positive reference on developing its fundamental research and key technology.

Contents

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1. Introduction

Carbon dioxide (CO_2) has been regarded as one of the most important greenhouse gases (GHGs). Anthropogenic CO_2 emissions from fossil fuel utilization especially from coal combustion make a significant contribution to global warming [1]. It has become an important issue in the fields of science, environment and even international economics and politics in recent years.

To effectively reduce the post-combustion CO_2 emission, the stable, safe and environmentally acceptable post-combustion CO_2 capture technologies are necessary in addition to improving energy efficiency and developing renewable energies. According to the capture mechanism, post-combustion CO_2 capture methods can be roughly categorized as chemical absorption, physicochemical adsorption, membrane, cryogenics, chemical looping combustion (CLC) and biotechnology (e.g., terrestrial vegetations or hydroponic algae). From a technical point of view all of these methods are feasible in spite of the differences in capture efficiency and capture capability. However, from an economical point of view, some of the physical and chemical methods mentioned above have to face serious challenges such as high energy consumption for regeneration (e.g. amine), large space requirements and difficult resourcelization for products. Moreover, from an environment-friendly point of view deep oceanic or geological storages may have the venture for CO_2 leakage over long time [2].

Biologic fixation via microalgae has been regarded as a potential and promising new method for post-combustion CO_2 capture and storage [3,4]. Fig. 1 shows a flowchart for a microalgal-CO_2 fixation and biomass production system. Biological fixation and storage of CO_2 via microalgae are essentially photosynthesis, which can convert water and CO_2 into organic compounds without additional or extra energy consumption and without secondary pollution. Compared with other carbon capture and storage (CCS) methods, microalgal-CO_2 fixation has a lot of advantages, such as wide distribution, high photosynthesis rate, fast growth rate, good environment adaptability and low cost of operation. As an extra benefit, microalgal biomass for energy use is produced after the CO_2 capture by microalgae.

In the microalgal-CO_2 fixation technology, performances of microalgal-CO_2 fixation and biomass production heavily depend on the culture process conditions, e.g., microalgal growth under combustion flue gas conditions is usually more complex than those under the conditions of the atmospheric environment. Besides microalgal species, the factors influencing microalgal-CO_2 fixation usually include physicochemical parameters (e.g., CO_2 concentration, toxic pollutants in combustion flue gas, initial inoculation density, culture temperature, light, nutrients and pH) and hydrodynamic parameters (e.g., parameters of flow, mixing and mass transfer, etc.). Although microalgal-CO_2 fixation and biomass conversion is becoming a research focus, most researches particularly concerned about

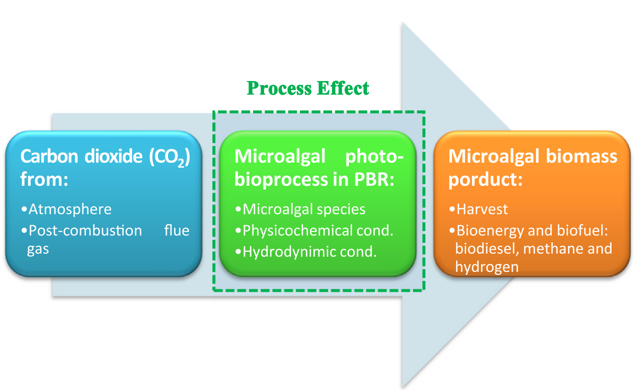


Fig. 1. Flowchart of microalgal-CO_2 fixation and biomass production.

carbon fixation strategy, photobioreactor design, conversion technology from microalgal biomass to bioenergy [5–16] and technique-economic evaluation for microalgal energy [17,18]. A completed and systematical review regarding the effect of process characteristics especially in the complex flue gas environment has not yet been reported up to now.

This work attempts to summary and review the state-of-the-art advances on microalgal-CO_2 fixation and biomass production, particularly focusing on the principle and process of carbon fixation, and the effect of microalgal species, physicochemical process parameters and hydrodynamic process parameters on microalgal-CO_2 fixation and biomass production. The challenges and prospects are also discussed.

2. Photobiochemical principle and process

2.1. CO_2 concentrating mechanism (CCM) process

As similar as other photosynthetic organism, microalgae concentrate or store CO_2 through a Calvin–Benson cycle, a redox reaction, in which the photosynthesis needs to be supplied with both a source of energy to drive this process, and the electrons to convert carbon dioxide into a carbohydrate. Especially for unicellular microalgae, CO_2 concentrating mechanism (CCM) plays a vital role during carbon fixation process as it can enhance the level of CO_2 at the active site of ribulose bisphosphate carboxylase-oxygenase (Rubisco) by transporting inorganic carbon or carbon dioxide into the cell. CCM directly results in the increase of photosynthetic rate and the decrease of the photorespiration [19–21].

A typical CCM process in microalgae can be illustrated in Fig. 2 (a), although there are a few differences in CCM for different typical microalgae such as *Cyanobacteria*, *Chlorophyta* and red *chromist* algae. [22]. Usually, dissolved inorganic carbon (DIC) exists in water in the form of CO_2, HCO_3^-, CO_3^{2-} and H_2CO_3 when the dynamic ionization equilibrium is reached, but only CO_2 and HCO_3^- are the main DIC forms which can be used by microalgal cells in different ways. For instance, both HCO_3^- and CO_2 can be simultaneously used by most of microalgae [23,24]. HCO_3^- has been demonstrated to be used not only via a direct way, e.g., active transport [25,26] and cation exchange [27,28], but also via an indirect way which catalyzes HCO_3^- as CO_2 and OH^- by perplasmic carbonicanhydrase (pCA) [29–33]. However, there is an exception that only CO_2 can be used by some microalgae [34,35].

During the process of DIC conversion, Carbonic anhydrase (CA) and pyrenoid play the vital role in microalgal CCM. CA includes Perplasmic Carbonic anhydrase (pCA), Cytosolic Carbonic Anhydrase (cyCA) and chloroplast carbonic anhydrase (chCA). The function of pCA is to keep the balance between CO_2 and HCO_3^- and continuously supply CO_2 for cells [20,36], and cyCA may accelerate the transport of CO_2 and HCO_3^- from plasma membrane to chloroplasts [23,36]. chCA is considered as the most important CA in CCM. Pyrenoid is also considered to be the other component of the CCM for unicellular green microalgae. Using biochemistry methods it has been found that pyrenoid mainly consisted of Rubisco [37]. Since the anhydrase in microalgal cells are liable to be influenced by the process factors, it can be inferred that these factors actually act on microalgal CCM.

2.2. Photosynthesis process

Microalgal photosynthesis is a physicochemical process that converts carbon dioxide into organic compounds using light energy and release molecular oxygen [38]. Frequently, the following empirical equation is used to describe the overall reaction of

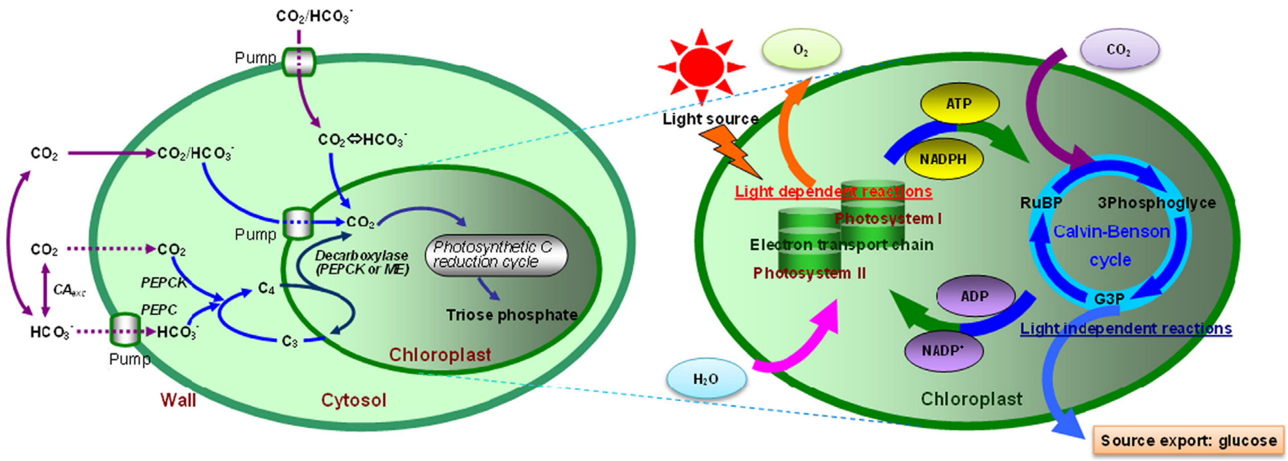


Fig. 2. Photobiochemical principles of microalgal-CO_2 fixation: (left) typical carbon concentrating mechanism [22] and (right) photosynthesis process [40].

photosynthesis:

$$6CO_2+6H_2O \overset{\text{Light Energy }(h\nu)}{\Longrightarrow} C_6H_{12}O_6+6O_2 \quad (1)$$

In this reaction, the standard free energy for the synthesis of glucose is 2870 kJ/mol [39].

Usually, photosynthesis has been regarded to occur in main stages (Fig. 2(b)): light dependent reactions and light independent reactions. The light dependent reactions capture the light energy and convert ADP and NADP+ into the energy carriers ATP and NADPH via the electron transport chain and produce oxygen. In this process, Antenna complexes formed by Chlorophyll and other carotenoids transfer light energy to P700 (part of Photosystem I) or P680 (part of Photosystem II), which are the different photochemical reaction centers located on the thylakoid membrane of the chloroplast. Excited electrons are transferred to electron acceptors, leaving the reaction center in an oxidized state [14,40]. Then, the light independent reactions capture carbon dioxide and produce the precursors of carbohydrates using previously formed ATP and NADPH by the Calvin–Benson cycle.

3. Effects of microalgal species

Besides the culture conditions microalgal species are most vital as they directly influence the performances carbon fixation and biomass production. Table 1 gives the effect of typical energy-microalgal species on the parameters of microalgal growth characteristic, biomass production and carbon fixation. Fig. 3 shows the relationship between microalgal species and maximum biomass production rate as well as maximum CO_2 fixation rate.

CO_2 fixation and biomass production performances vary with microalgal species, although the data may not have a strict comparability as microalgae have different biological performance and were cultured in different conditions. However, compared with other species (e.g., Cyanophytes and Chrysophyte), Chlorella were observed to have a better performance. The biomass production rate and carbon fixation rates were up to 1.060 g/L/d and 1.992 g/L/d, respectively.

Compared with atmospheric-CO_2 culture process, several harsh conditions such as high CO_2 concentration, high aeration ratio (aeration load) and toxic pollutants in flue gas have negative impacts on the growth of microalgal species. However, these effects may be overcome for some microalgal species by adaption, making it possible to endure the rigorous flue gas conditions and continue growing [68–73]. Few microalgae were even able to tolerate a high level CO_2 concentration up to 70% [50,55,74,75] or even 100% [42], high aeration rate of 2.0 vvm [46], low pH value of less than 3.5 [56] and toxic compounds with 100 ppm SO_2 and NO_x [53]. Additionally, effects of nutrient source, light intensity, culture temperature on micaoalgal growth are also related to microalgal species. Optimal ranges or values of these parameters to achieve high CO_2 fixation rates and biomass productions are usually different for each microalgal species.

It is necessary to develop the high performance species to realize the maximization of microalgal CO_2 fixation and biomass production in more complex and harsh environments. Most of microalgal species are isolated from natural streams, lakes or oceans and pre-adapted for the living environment through artificial domestication, and have been successfully used for fixation of atmospheric CO_2 [76]. However, unlike atmospheric air with extremely low CO_2 (about 0.038% v/v), actual post-combustion flue gas has the features of high CO_2 concentration (10–20% or more v/v), high flow rate, high temperature (80–120 °C or above) and toxic compounds (SO_x, NO_x and mercury). It means that the microalgal species will be required to have ability for post-combustion CO_2 fixation [77–79]. Therefore, selection, isolation and culture of microalgal species with fast growth rate, high photosynthetic rate, strong environmental tolerance/adaptability and high lipid content will be future research and development directions. Moreover, the general microalgal species for industrial application are obtained using natural breeding method. Usually, they do not have outstanding performance. To enhance and improve microalgal-CO_2 fixation and biomass production, it is also important to introduce the high-performance microalgal species using advanced breeding methods such as physicochemical mutation, cellfusion/genetic improvement and crossbreeding [80].

Microalgal-CO_2 biofixation and biomass production is a complex physicochemical process especially in cases of flue gas environment. Therefore, besides microalgal species the process must be influenced by culture parameters including physicochemical and hydrodynamic parameters. To improve the ability of microalgal carbon sequestration and the efficiency of biomass production, it is important to insight into the impacts of these factors and to further optimize these parameters.

4. Effects of physicochemical process

4.1. CO_2 concentration

It was demonstrated that the growth performance for some microalgal can be negatively affected when suffering from CO_2 with higher than 1% (v/v) concentration [57]. However, for other microalgae especially for energy microalgae CO_2 concentration has a complex effect on microalgal carbon biofixation and biomass

Table 1
Summary of microalgal biomass production and CO_2 fixation parameters under different process conditions[a].

Microalgal species[b]	CO_2 (%, v/v)	AR (vvm)	ID (g/L)	LI (umol/m^2/s)	L/D (h/h)	T (°C)	N (mg/L)	P (mg/L)	pH (–)	PBR[c]	OS[d]	V&S	CM	SGR[e] (1/d)	BPR[f] (g/L/d)	CFR[g] (g/Ld)	Ref.
NS1	15	NA	0.18	168	24/0	25	NA	NA	6.3	RB	Batch	$V=1$ L	Mf/2	0.700	0.256	0.482	[41]
NS2	15	NA	0.18	168	24/0	25	NA	NA	6.3	RB	Batch	$V=1$ L	Mf/2	0.657	0.229	0.431	
PT	15	NA	0.18	168	24/0	25	NA	NA	6.3	RB	Batch	$V=1$ L	Mf/2	0.501	0.180	0.338	
CS T-1	15	0.83	0.002–0.005	110	NA	30–45	NA	NA	NA	SF	Batch	$V=0.6$ L	Fitzgerald	0.915–3.289	0.009–0.106	0.130	[42]
	0.038–100	0.83	0.03	110	NA	35	NA	NA	4.8–10.7	SF	Batch	$V=0.6$ L	Fitzgerald	0.542–0.840	0.084–0.394	0.158–0.741	
C A-2	20	NA	NA	500	NA	30–40	12.38	9.19	6.0 (initial)	BF	Batch	$V=0.3$ L	MC	0.773–2.411	NA	NA	[43]
C H-84	5–40	NA	NA	500	NA	40	12.38	9.19	6.0 (initial)	BF	Batch	$V=0.3$ L	MC	1.417–1.599	NA	NA	
CL	20	0.2	NA	250	24/0	25	NA	NA	NA	NA	NA	$V=4$ L	NA	0.078	0.400	0.752	[44]
NOA-113	15	0.036	0.4	174.4	12/12	25	70.00	5.17	<6.0	LT	Batch	$V=4$ L, $D\times L=5\times 2500$ cm	Mf/2	0.309	0.358	0.674	[45]
CV UTEX259	0.038–20	2	0.1	110	24/0	27	138.61	168.68	7.2–5.4	BC	Batch	$V=0.4$ L	N-8	0.216–0.385	0.067–0.344	0.063–0.648	[46]
CS HA-1	10	0.3	0.3	51.4	12/12	28	693.07	284.93	6.0 (initial)	HT	Batch	$D\times L=1.6\times 2700$ cm	M4N	0.399	0.569	1.070	[47]
IG(F)	0.038	NA	0.137	115	12/12	18	4-Nitrate	NA	NA	BC	Batch	NA	NA	0.207	0.126	0.236	[48]
	0.038	NA	0.137	115	12/12	18	4-Nitrite	NA	NA	BC	Batch	NA	NA	0.195	0.117	0.220	
	0.038	NA	0.137	115	12/12	18	4-Urea	NA	NA	BC	Batch	NA	NA	0.183	0.100	0.187	
PP1380-1 A	2	0.04	0.075	120	14/10	25	20.00		7.0 (initial)	PST	Batch	$V=50$ L, $D\times L=2.4\times 8400$ cm	Hemerick	0.250	0.304	0.572	[49]
CS KR-1	10–70	1	0.1	200	24/0	25	693.07	284.93	6.0–3.5	BC	Batch	$V=0.2$ L, $D\times H=3.5\times 40$ cm	M4N	0.336–0.671	0.108–0.917	0.204–1.723	[50]
IG(P)	0.038	NA	0.001	183.6	24/0	20	12.35	1.29	NA	EF	Batch	$V=1.0$ L	f/2	0.645	0.011	0.020	[51]
CC	0.038	NA	0.001	183.6	24/0	20	12.35	1.29	NA	EF	Batch	$V=1.0$ L	f/2	0.387	0.007	0.014	
CV(D)	0.038	0.45	0.45	980	1/10	29	693.07	170.96	6.8 (initial)	BC	Batch	$V=3.0$ L	DS	0.293	0.436	0.819	[52]
	0.038	0.45	0.25–0.60	980	1/10	29	693.07	170.96	6.8 (initial)	FPA	Batch	$V=3.0$ L	DS	0.339–0.416	0.543–0.840	1.021–1.579	
CS KR-1	15	0.5	0.1	450	24/0	25	693.07	284.93	5.6–7.2	WB	Batch	$V=0.05$ L	M4N	1.547	1.400	2.632	[53]
CV(J)	0.038–30	NA	0.02	58.8	NA	25	28.00	6.09	NA	EF	Batch	$V=0.1$ L	N-8	0.528–0.745	0.092–0.387	0.174–0.727	[54]
C ZY-1	0.038–70	0.25	0.1	140	12/12	25	693.07	284.93	7.0–3.0	BC	Batch	$V=1.0$ L	M4N	0.347–0.677	0.117–0.950	0.219–1.768	[55]
EG	10	0.03	0.03	480	24/0	28	212.12	227.94	3.5 (initial)	BC	Semi-C	$V=100$ L,. $L\times W\times H=90\times 20\times 70$ cm	MC	0.599	0.114	0.214	[56]
CV(C)	0.1–2.8	0.3	1.644	200	12/12	25–30	13.86	2.28	NA	HMF	Cont.	$V=10$ L,.$D\times H=11\times 110$ cm	NA	NA	0102–1.060	0.192–1.992	[57]
SO	0.038–18	0.3	0.15	44.8	12/12	30	173.27	284.93	7.4–5.3	CF	Batch	$V=1.8$ L	MC	0.216–0.261	0.064–0.090	0.120–0.169	[58]
CK	0.038–18	0.3	0.15	44.8	12/12	30	34.65	17.10	8.7–6.4	CF	Batch	$V=1.8$ L	BM	0.199–0.257	0.061–0.090	0.115–0.169	
SS(D)	0.038–12	0.3	0.15	44.8	12/12	30	173.27	284.93	7.08–10.22	BC	Batch-3S	$V=3\times 1.8$ L, $D\times H=6.5\times 60$ cm	MZarrouk	0.330–0.440	0.040–0.200	0.075–0.376	[59]
SO	0.038–12	0.3	0.15	44.8	12/12	30	173.27	284.93	6.95–10.03	BC	Batch-3S	$V=3\times 1.8$ L, $D\times H=6.5\times 60$ cm	MC	0.150–0.220	0.040–0.140	0.075–0.263	
CS(C)	0.038–5	0.25	0.011–0.113	300	24/0	26	46.33	4.76	NA	BC	Batch	$V=0.8$ L, $D\times H=7\times 30$ cm	Mf/2	0.127–0.605	0.074–0.207	0.017–0.389	[60]
AMN	15	1	0.1	150	24/0	35	24.71	7.13	8.0–8.7	BC	Batch	$V=2.4$ L, $D\times H=7\times 70$ cm	BGN	0.605	0.769	1.446	[61]
	15	1	0.1	150	24/0	35	24.71	7.13	8.0–9.0	AL	Batch	$V=2.4$ L, $D\times D_i\times H=7\times 1\times 70$ cm	BGN	0.611	0.800	1.504	
AMN	15	1	0.1	150	24/0–2/22	35	24.71	7.13	8	BC	Batch	$V=3.0$ L, $D\times H=7.5\times 75$ cm	BGN	0.067–0.605	0.008–0.769	0.016–1.446	[62]
CS AG10002	0.5–5	0.1	0.01	100	24/0	20	17.65	0.29	7.2 (initial)	BC	Batch	$V=0.6$ L, $D\times H=4.6\times 46$ cm	Allen	0.792–0.885	0.192–0.335	0.360–0.630	[63]

	0.5	0.06–0.40	0.01	100	24/0	20	17.65	0.29	7.2 (initial)	BC	Batch	$V=0.6$ L, $D\times H=4.6\times 46$ cm	Allen	0.879–0.933	0.323–0.448	0.608–0.843	
CV(S)	10	1.06	0.2	68	24/0	22	2.25–123.53	13.36	6.0 (initial)	CF	Batch	$V=0.1$ L	3N-BBM+V	0.077–0.181	0.033–0.278	0.063–0.522	[64]
	10	1.06	0.1–0.8	68	24/0	22	0.00	13.36	NA	CF	Batch	$V=0.1$ L	3 N-BBM+V	0.051–0.070	0.008–0.083	0.016–0.157	
BB	10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.027	0.050	[65]
CV(Y)	10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.105	0.197	
SS(Y)	10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.218	0.409	
CS WT	2–25	0.05	0.2	300	24/0	25	37.06	3.88	NA	BC	Batch	$V=0.8$ L, $D\times H=7\times 30$ cm	Mf/2	0.276–0.324	0.142–0.200	0.266–0.376	[66]
CS MTF-7	2–25	0.05	0.2	300	24/0	25	37.06	3.88	NA	BC	Batch	$V=0.8$ L, $D\times H=7\times 30$ cm	Mf/2	0.312–0.411	0.183–0.358	0.345–0.674	
CS(Z)	10–20	0.2	0.15	84	12/12	18	12.35	1.29	8.0–5.2	BC	Batch	$V=1.0$ L, $D\times H=6.5\times 40$ cm	f/2	0.297–0.374	0.150–0.271	0.282–0.510	Present work

[a] CO_2=carbon source, AR=aeration ratio, ID=initial biomass density, LI=light intensity, L/D=light–dark circle, T=temperature, N=Nitrogen source, P=phosphorus source, PBR=photobioreactor, V&S=volume and size; OS=operating strategy, CM=culture medium, SGR=special growth rate of microalgal biomass, BPR=Biomass production rate, CFR=CO_2 fixation rate.

[b] NS1=*Nannochloris* sp., NS2=*Nannochloropsis* sp., PT=*Phaeodactylum tricornutum*, CS T-1=*Chlorella* sp. T-1, C A-2=*Chlorella* A-2, C H-84=*Chlorella* H-84, CL=*Chlorococcum littoral*, NOA-113=NOA-113, CV UTEX259=*Chlorella vulgaris* UTEX259, CS HA-1=*Chlorella* sp. HA-1, IG(F)=*Isochrysis galbana*, PP 1380-1A=*Porphyridium purpureum* 1380-1A, CS KR-1=*Chlorella* sp. KR-1, IG(P)=*Isochrysis galbana*, CC=*Chaetoceros calcitrans*, CV(D)=*Chlorella vulgaris*, CS KR-1=*Chlorella* sp. KR-1, CV(J)=*Chlorella vulgaris*, C ZY-1=*Chlorella* ZY-1, EG=*Euglena gracilis*, CV(C)=*Chlorella vulgaris*, SO=*Scenedesmus obliquus*, CK=*Chlorella kessleri*, SS(D)=*Spirulina* sp., SO=*Scenedesmus obliquus*, CS(C)=*Chlorella* sp., AMN=*Aphanothece microscopica Nägeli*, CS AG10002=*Chlorella* sp. AG10002, CV(S)=*Chlorella vulgaris*, BB=*B. braunii*, CV(Y)=*C. vulgaris*, SS(Y)=*Scenedesmus* sp., CS WT=*Chlorella* sp. WT, CS MTF-7=*Chlorella* sp. MTF-7, CS(Z)=*Chlorella* sp.

[c] RB=Roux bottles, SF=spinner flask, FB=bubbled flask, LT=long tubular, BC=bubble column, HT=helical tubular, PST=pilot-scale tubular, EF=Erlenmeyer flasks, FPA=flat plate airlift, WB=washing bottle, CF=conical flask, T=tubular, HFM=hollow fiber membrane, AL=air-lift.

[d] Batch=batch, Semi-C=semi-continuous, Cont.=continuous, Batch-3S=batch with three stages.

[e] Calculated by $SGR=(\ln X_t-\ln X_0)/(t-t_0)$.$X$ is microalgal biomass concentration (g/L) and t is time (d).

[f] Calculated by $BPR=(X_t-X_0)/(t-t_0)$.

[g] Calculated by CFR=1.88 × BPR, which is obtained based on typical microalgal molecular $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ [67,14].

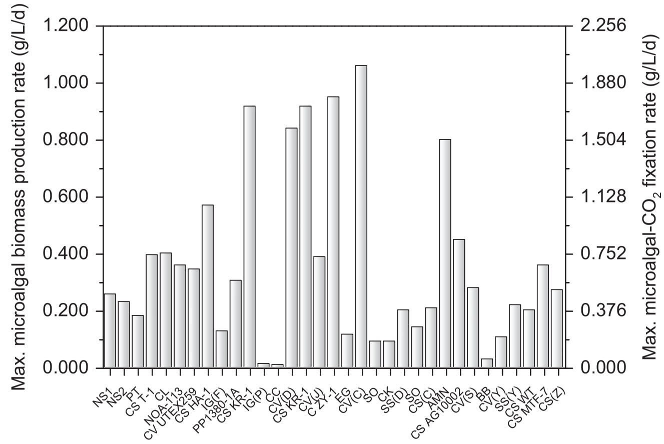


Fig. 3. Relationship between microalgal species and its maximum microalgal-CO_2 fixation rate as well as biomass production rate under different process conditions.

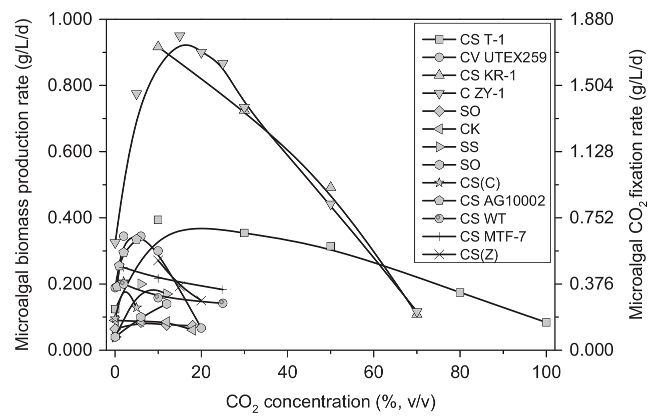


Fig. 4. Effect of CO_2 concentration on microalgal-CO_2 fixation and biomass production. NS1=*Nannochloris* sp., NS2=*Nannochloropsis* sp., PT=*Phaeodactylum tricornutum*, CS T-1=*Chlorella* sp. T-1, C A-2=*Chlorella* A-2, C H-84=*Chlorella* H-84, CL=*Chlorococcum littoral*, NOA-113=NOA-113, CV UTEX259=*Chlorella vulgaris* UTEX259, CS HA-1=*Chlorella* sp. HA-1, IG(F)=*Isochrysis galbana*, PP 1380-1 A=*Porphyridium purpureum* 1380-1 A, CS KR-1=*Chlorella* sp. KR-1, IG(P)=*Isochrysis galbana*, CC=*Chaetoceros calcitrans*, CV(D)=*Chlorella vulgaris*, CS KR-1=*Chlorella* sp. KR-1, CV(J)=*Chlorella vulgaris*, C ZY-1=*Chlorella* ZY-1, EG=*Euglena gracilis*, CV(C)=*Chlorella vulgaris*, SO=*Scenedesmus* obliquus, CK=*Chlorella kessleri*, SS(D)=*Spirulina* sp., SO=*Scenedesmus* obliquus, CS(C)=*Chlorella* sp., AMN=*Aphanothece microscopica Nägeli*, CS AG10002=*Chlorella* sp. AG10002, CV (S)=*Chlorella vulgaris*, BB=*B. braunii*, CV(Y)=*C. vulgaris*, SS(Y)=*Scenedesmus* sp., CS WT=*Chlorella* sp. WT, CS MTF-7=*Chlorella* sp. MTF-7, CS(Z)=*Chlorella* sp.

production performances (Fig. 4). Most of microalgae grow only at low CO_2 concentrations level, and would be inhibited when CO_2 concentration level was higher than 5% (v/v) [81,82]. Some microalgae can grow under higher flue gas-CO_2 concentrations level (10–15%), but the carbon fixation and biomass production rate are less than that under lower CO_2 concentration. Very few microalgal species are able to tolerate extremely high CO_2 level up to 70% (e.g., CS KR-1 and C ZY-1) and even 100% (e.g. CS T-1).

Essentially, microalgal growth and its CO_2 fixation are strongly related to CCM [83]. High concentrations of CO_2 (even more than 1%, v/v) significantly inhibited CA activity and CCM microalgae cell formation has a significantly negative effect on activity of CA. When increasing CO_2 concentration the hydrolysis of CO_2 moves to the direction of the positive reaction, resulting in the increase of HCO_3^- and H^+ concentration which decrease the pH value in the medium. Low pH value may inhibit the activity of carbonic anhydrase (CA), which plays an important catalytic role in interchange between CO_2 and HCO_3^- and is regarded as an important

factor of CCM. As a result, the microalgal performance on carbon biofixation is weakened.

However, according to the analysis of effects of CO_2 concentration on cellular morphology, photosynthetic physiology and molecular biology (e.g. cell vacuoles, CA and RuBisCO), when the increase of CO_2 concentration gives rise to the decreases of the pH value in the medium, some microalgal cell was able to adapt to the coercion of high concentration CO_2 [84] through different methods, e.g., gene regulation and increasing the energy allocation proportion PSI/PSII. These methods can temporarily reduce the synthesis of organic carbon and simultaneously provide more ATP to maintain the pH stability inside the cell. This is why they were able to tolerate extremely high CO_2 concentration.

The optimal CO_2 concentration for most microalgal species was usually recommended to be 0.038–10%, e.g., the maximum biomass production was observed at 2.5% CO_2 for microalgae CS(C) [60] while at 6% for SO and CK [58]. Although the optimal CO_2 concentration levels for microalgal growth varied with microalgal species, the effect of CO_2 at lower concentrations was more pronounced than at higher ones [9].

4.2. Toxic pollutants in combustion flue gas

4.2.1. SO_2

The presence of SO_2 has a strongly inhibited effect on microalgae growth (Table 2). When SO_2 concentration exceeds 100 ppm, it is almost impossible to grow for most of microalgae [85]. Some microalgal species are able to grow difficult in the condition of high SO_2 concentration, but they have a longer lag phase than that without SO_2 presence. With the increase of SO_2 concentration, the inhibited effect can be enhanced, resulting in a sharp reduction in carbon fixation and biomass production, e.g., even *Chlorella* sp. KR-1 which was regarded as a high-performance microalgal species could not survive under the condition of 150 ppm SO_2 with 15% CO_2 [86].

Table 2
Effect of toxic pollutants in flue gas on microalgal-CO_2 fixation and biomass production[a].

Microalgal species[b]	CO_2 (%) /SO_2 (ppm)/NO (ppm)	SGR (1/d)[c]	BPR (g/L/d)[d]	CFR (g/Ld)[e]	Ref.
NS1	15/0/0	0.700	0.256	0.482	[41]
	15/50/0	0.683	0.245	0.461	
	15/0/300	0.268	0.077	0.146	
NS2	15/0/0	0.657	0.229	0.431	[41]
	15/50/0	0.619	0.207	0.390	
	15/0/300	0.344	0.098	0.184	
CS T-1	15/10/30	0.978	0.368	0.691	[42]
	15/5/15	1.009	0.418	0.785	
	15/20/60	1.050	0.493	0.926	
	15/50/150	NA	NA	NA	
	15/80/240	NA	NA	NA	
NOA-113	15/0/0	0.309	0.358	0.674	[45]
	15/0/100	0.292	0.317	0.595	
	15/0/300	0.288	0.308	0.580	
CS HA-1	10/0/0	0.399	0.569	1.070	[47]
	10/0/100	0.310	0.160	0.301	
CS KR-1	15/0/0	1.547	1.400	2.632	[53]
	15/60/0	1.353	0.889	1.671	
	15/100/0	1.157	0.556	1.044	
	15/150/0	NA	NA	NA	
CS KR-1	15/0/0	1.519	1.311	2.465	[53]
	15/0/100	1.465	1.156	2.172	
	15/0/300	NA	NA	NA	
EG	10/0/0	0.599	0.114	0.214	[56]
	10/5/26	0.636	0.138	0.259	
CS WT	23/87/78	0.352	0.242	0.454	[66]
CS MTF-7	23/87/78	0.421	0.383	0.721	[66]

[a] SGR = special growth rate of microalgal biomass, BPR = Biomass production rate, CFR = CO_2 fixation rate.
[b] NS1 = *Nannochloris* sp., NS2 = *Nannochloropsis* sp., CS T-1 = *Chlorella* sp. T-1, NOA-113 = NOA-113, CS HA-1 = *Chlorella* sp. HA-1, CS KR-1 = *Chlorella* sp. KR-1, EG = *Euglena gracilis*, CS WT = *Chlorella* sp. WT, CS MTF-7 = *Chlorella* sp. MTF-7.
[c] Calculated by $SGR = (\ln X_t - \ln X_0)/t - t_0.X$ is microalgal biomass concentration (g/L) and t is time (d).
[d] Calculated by $BPR = (X_t - X_0)/(t - t_0)$.
[e] Calculated by CFR = 1.88 × BPR, which is obtained based on typical microalgal molecular $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ [67,14].

Actually, SO_2 may not directly inhibit the microalgal growth [87]. The inhibition effects of SO_2 on microalgae growth can be essentially attributed to the effect of pH value. The H^+ release produced by hydrolysis of SO_2 cause a reduction in pH of the culture medium [88], thereby indirectly affecting the normal conduct of the CCM and even killing the microalgae cells at last when the pH was below 3.0 [42]. However, if pH of the culture medium is artificially controlled as constant by neutralization method, the microalgal growth characteristic is almost the same without the presence of SO_2 [75]. It seems to indirectly demonstrate that the effect of SO_2 on microalgae is achieved through pH value in the batch strategy. However, this situation is not seen in all occasions. Other investigations indicated that the suppression effect of SO_2 on microalgae is associated not only with pH value (H^+ concentration in the culture medium) but also with $SO_4{}^{2-}$ and $HSO_4{}^-$ also from SO_2 hydrolysis, suggesting that $SO_4{}^{2-}$ and $HSO_4{}^-$ are inhibition factors of mciroalgal growth [66].

4.2.2. NO_x

In actual flue gas, the total NO_x emission level varies from several hundreds to thousands ppm with more than 90–95% NO and 5–10% NO_2. After flue gas de-NO_x process the NO still at the level of 50–200 ppm. Unlike water-soluble SO_2 which result in significant decrease of pH in the culture medium, NO is hard to directly impact the growth of microalgae via pH in the culture medium [45]. However, the presence of NO is associated with microalgae cells physiological conditions. Its concentration usually has two-side influence on growth of microalgae. This influence is also closely related to microalgal species. Extremely low concentrations NO may even be absorbed by the culture medium and transformed into $NO_2{}^-$ as the source of nitrogen nutrition of microalgae in the process of using inorganic forms [9]. However, this positive influence is quite limited: the increased NO concentration results in at least the decreased growth rate of microalgae for most of microalgal species; NO with higher than 300 ppm may give rise to the decline of microalgae [53] (Table 2).

4.2.3. Mercury

As one of the most important trace metals emitted from coal-fired power stations, mercury exists in three primary forms in post-combustion flue gas: elemental mercury (Hg^0), oxidized mercury (Hg^{2+}) and particle-bound mercury (Hg_p). Usually, Hg_p can be separated by high-efficiency particle collector such as FF or ESP. Due to its water-indissolvability, Hg^0 often is oxidized to Hg^{2+} and then removed by washing methods in many mercury control technologies. Until now the effect of Hg^0 on microalgae was almost not involved at all while Hg^{2+} had been experimentally investigated. It is observed that microalgal growth rate can be inhibited even though Hg^{2+} concentration was at an extremely low level. Naturally, trace metal ion plays the destructive role on chlorophyll. With the increasing concentration of Hg^{2+} the Chlorophyll content decreased gradually, directly causing the reduction of photosynthetic efficiency [89].

4.3. Initial biomass concentration

As similar as other microbian growth process, most microalgal growth in batch culture has four different growth stages: lag

phase, exponential or log phase, stationary phase and death phase. Microalgal growth characteristic can be estimated by two models a first-order dynamic model called as "*J*" curve in the log phase (in this case the microalgal biomass concentration at the end of the lag phase is close to the initial inoculation concentration):

$$dX/dt = \mu X \tag{2a}$$

Or a Logistic model called as "*S*" curve in the whole phases:

$$dX/dt = \mu_{max} X(1 - X/X_{max}) \tag{2b}$$

Theoretically, microalgal biomass production or corresponding carbon fixation increases as the initial inoculation concentration increases under given conditioning factors and culture time. In the microalgal growth process, increase of initial biomass concentration can reduce CO_2 load and enhance the tolerance to CO_2 [60] and even toxic compounds such as SO_2 and NO, leading to increased biomass production [90], e.g., when the initial culture density increased to 0.3 g/l, *Chlorella* sp. cells could grow well with 100 ppm SO_2 and 300 ppm NO [45,53,86,91,92]. Additionally, for some microalgal species, the short lag phase and steep log phase could be observed with a high initial concentration [60]. However, increasing initial concentration can intensify the competition among microalgae for nutrients uptake, light, and other conditioning factors when they are insufficient. In contrast, high initial biomass concentration increases the carbon fixation and biomass production while nutrients source and light conditions are sufficient. In addition, it should be noted that initial biomass concentration usually has an interactive influence on the microalgal growth with other conditioning factors such as C source, N source, light intensity and temperature, which are decisive to the special growth characteristics. Therefore, there is a complex relationship between initial inoculation density and special growth.

4.4. Culture temperature

As expected, culture temperature is an important conditioning factor to microalgal-CO_2 biofixation and biomass production because microalgal photosynthesis is naturally a series of temperature-dependent physicochemical reaction processes. Generally, the effect of temperature on microalgal growth can be evaluated by a quasi-parabola opening down. The low temperature is not in favor of enhancing the activity of Rubisco, thereby the process of photosynthesis and CCM will not be accelerated; while the extremely high temperature inhibits the microalgal metabolic behavior and respiration intensity [93], and also causes low CO_2 solubility in water according to Herry's law. Therefore, there is an optimal temperature value or range for microalgal growth. According to previous research results, most commonly microalgal species can tolerate temperatures between 15 and 26 °C [9]. The optimum temperature for microalgae varies with microalgal species and culture medium composition. An intermediate value of 18–20 °C close to room temperature was often recommended due to high growth rates under that. Moreover, the microalgal growth would be inhibited or the lag phase would be lengthened for most microalgal species when the culture temperature is far higher more than their optimal growth temperature [68,74].

Usually, temperatures lower than 16 °C will slow down microalgal growth, whereas those higher than 35 °C are usually lethal for a number of microalgal species. However, the tolerance and adaptability of some microalgae to high temperature can be improved by the induced acclimation technology, e.g., the domesticated species *Chlorella* sp. T-1 had an optimal growth temperature of 35 °C [42] while *Chlorella* KR-1 [74] and ZY-1 [55] were able to grow at the temperature up to 40 °C, and even with high special growth rate.

4.5. Light

For the microalgal biofixation of CO_2 from combustion flue gas, the light source can be usually divided into natural sunlight which is applied in both open and closed cultivation, and artificial cold light which is mainly applied in closed cultivation. No matter what type of light source, light is the most influencing factor to microalgal carbon sequestration and biomass production because of the photoautotrophic characteristics of microalgae. Usually, the effect of light is presented in two ways: light intensity and light–dark periods and cycles.

There is complex relationship between light intensity and microalgal growth. In the light-limited area, photosynthesis rate increases as light intensity increased. Regarding the light intensity as only single factor, its effect on special growth rate for microalgae can be described by the following semi-empirical model:

$$\mu = \mu_{max} I^n / (I^n + K_I^n) \tag{3a}$$

$$\mu = \mu_{max} I / (I^2 + I + K_I) \tag{3b}$$

where K_I is half-saturation constant for light intensity (μE/m^2/s).

With continuous increase of light intensity, microalgal photosynthesis has an increasing rate but a gradually reduced acceleration. Light intensity at maximum photosynthesis rate is called the saturated light intensity after that the light-saturated area is reached. After light-saturated area photosynthesis can be weakened and inhibited with increased light intensity (also called photoinhibition). Similarly, the minimum limit of the light-limited area is called as compensated light intensity. It should be noted that the light-limited range also varies with microalgal species [74]. The most often employed light intensities range between 100 and 200 μE/m^2/s. In addition, the effect of light intensity on microalgal growth must take into account the interactions between the various influencing factors, e.g., culture temperature is able to adjust the required light intensity by affecting the metabolic reaction of microalgal cells. Specifically, under higher culture temperature microalgae may well grow with lower light intensity requirement. Microalgal photosynthesis can also be enhanced as the nutrient concentrations increased under high light intensity while it can be weakened when the cell density (biomass) increased under low light intensity.

Besides light intensity, it was found that light–dark periods and cycles could also influence the microalgal growth significantly [94]. The light–dark periods for most microalgal cultivation include 24 h:0 h (Although some microalgal species do not grow well under constant illumination), 16 h:8 h and 12 h:12 h. For a specified microalgal species, there are different growth characteristics under different light–dark periods. The experiment indicated that the photosynthetic efficiency could be decreased when the dark period was up to 50% of the cycle period (12 h:12 h) [14]. Moreover, due to the difference of photobioreactor configuration, the light distribution and light–dark cycle are also influenced by fluid-cell flow and inter-cell absorption and scattering to light, resulting in effects on the whole processes of microalgal CCM and photosynthesis [95].

4.6. Nutrients

Besides trace metals and vitamins, N and P are the two most important nutrients in the culture medium to maintain the microalgal growth. As a constituent of both nucleic acids and proteins, nitrogen is directly associated with the primary metabolism of microalgae [9]. Usually, in the culture medium for microalgal cultivation, nitrogen sources exist in the forms of nitrate (NO_3^-), nitrite (NO_2^-) and ammonia salt such as urea (NH_4^+); while phosphorus exists in the forms of hydrogen phosphate

(HPO_4^{2-}) and dihydric phosphate ($H_2PO_4^-$). Appropriate concentrations of N and P are able to effectively promote the microalgal growth. As expected, extremely low N and P concentrations would cause the microalgal growth inhibition while high N and P concentration would present toxic effects on microalgae, decreasing their growth rate and even causing death of them.

The effects of N and P on the microalgal growth as well as carbon fixation and biomass production are mainly attributed to the types of nitrogen source in addition to N concentration. When culturing *Isochrysis galbana* in nitrate, nitrite and urea medium, it was found that urea cultures showed significantly higher growth rate as well as more lipids than nitrate and nitrite medium which presented very similar trends with low growth rate [48]. In addition, high N/P ratio is helpful to increase the growth rate and biomass production under conditions of atmospheric CO_2 as the carbon source. Moreover, it should be noted that the N source has the interactive influence with other process factors particularly with the C source [96].

4.7. pH value

According to the microalgal CCM, most important DIC forms, CO_2 and HCO_3^-, are closely related to the pH value in the culture medium [58,59] as there are reversible chemical equilibriums. Besides chemical properties of culture medium, pH change in medium is attributed to the hydrolysis of CO_2 and water-soluble pollutants such as SO_2 from flue gas. Effects of pH on microalgal-carbon biofixation and biomass production mainly depend upon CO_2 and SO_2 concentration.

For atmospheric CO_2, there is no significant pH change in the culture medium. The pH ranges are about 7.9–8.3 for marine water and about 6.0–8.0 for freshwater. Because the CO_2 concentration in air is extremely low (0.038%), CO_2 uptake by microalgal cells can cause pH rising to more than 9.5–10 in this situation. However, for post-combustion flue gas, pH sharply reduced to about 5.5 as CO_2 has a high concentration of 10–20% or more. Additionally, 100–250 ppm SO_2 also makes the pH value in the flue gas reduced to about 3.5–2.5 at aeration rate of 0.25 vvm. Usually, low pH has an inhibited effect on Rubisco activity in the CCM, leading to the inhibition to microalgal growth. Most microalgal species have their own optimal pH ranges to grow (e.g., *Synechococcus* PCC7942 at pH 6.8 [97]). However, after habituated culture some microalgal species may be tolerated to extremely low pH values (e.g., *Chlorella* sp. KR-1 at pH below 4.0 [74]).

5. Effects of hydrodynamic process

5.1. Flow and mixing

Microalgal culture modes usually included the open (e.g., raceway ponds, lake, etc.) and closed cultivation (e.g., column, tubular and flat plate, etc.). Regardless of the microalgal photobioreactor (PBR) types used in these culture modes, appropriate turbulent flow and mixing in gas–liquid–solid (CO_2-medium-microalgae) phases are necessary and important to enhance mass transfer, to achieve light, temperature and nutrients equalization, to remove produced oxygen and to prevent the microalgal aggregation and sedimentation. However, excessive turbulent flow and mixing may lead to damage to microalgal cell because not all microalgal species can tolerate vigorous shear stress caused by flow turbulence.

Besides the jet pumping for open culture system, methods of flow and mixing in a microalgal PBR for closed culture system usually include mechanical stirring and gas aerating. For mechanical stirring, the effect of flow and mixing is directly associated with stirring speed. Especially, shear stress near the impeller has a maximum value which may cause a larger damage to microalgal cells. Currently, as a most widely used method, gas aerating (usually using bubbling) is able to provide a relatively good flow and mixing performance. Aeration rate is an important parameter besides the bubble size in the gas aerating method. It is defined as the gas volumetric flow rate per unit volumetric culture medium (vvm). As expected, an appropriate turbulence effect by an appropriate aeration rate is helpful to increase the microalgal performance on carbon fixation and biomass production, but extremely high aeration rate also gives rise to increase of shear stress especially in the processes of bubble generation, bubble deformation (e.g. bubble coalescence and break-up) and gas–liquid interface formation [98–100]. Moreover, the flow pattern by aeration can be improved using optimized PBR configuration, such as using horizontal and vertical baffles in flat plate airlift. [101]. Also, the turbulent mixing by aeration can be controlled via adequate use of baffles [9]. Recently, there were preliminary investigations using a computation fluid dynamics (CFD) technique to optimize the flow and mixing in PBR [102–104].

Usually, performance on microalgal-CO_2 fixation and biomass production was found to have a nonlinear relationship with aeration rate. For most closed cultivation, the recommended aeration rate is 0.10–1.00. The optimum aeration rate varies with microalgal species and PBR configuration, e.g., 0.025–1 vvm was proposed to be cost-effective for 5% or 10% (v/v) CO_2 aeration and 0.05 vvm for a flat-panel PBR [105]. Moreover, investigation indicates that the aeration strategy has an influence, e.g., gradual increase of CO_2 supply could enhance the growth rate and CO_2 fixation rate compared with constant CO_2 supply. This is because microalgae could adapt to the new CO_2 concentration well and enhance their CO_2 tolerance when CO_2 supply slowly increases, especially under a relatively higher concentration of CO_2 [46].

5.2. Mass transfer

There is a complex mass transfer process in a Microalgal-PBR. It involves a process of three-phase mass transfer contains mass transfer between: gas (CO_2)–liquid (medium), gas (CO_2)–solid (microalgae), and liquid (medium)–solid (microalgae). In the gas aerating method, mass transfer performance and biochemical reaction rate depend on bubble size, gas hold-up, gas–liquid contact area and CO_2 concentration and gas/liquid ratio, etc. In recent years, some new methods were used to improve mass transfer drive, including enhancing CO_2 concentration gradient (e.g., using $NaHCO_3$ as additive to generate chemical reaction), or expanding contact area (e.g., using hollow-fiber membrane PBR [106,107].

CO_2-medium mass transfer process is usually regarded as a gas–liquid absorption process. According to governing equations based on the two-film theory, mass transfer rate can be expressed as $dC_{CO_2}/dt = k_l a(C^*_{CO_2} - C_{CO_2})$, where k_l is the mass transfer coefficient based on liquid phase, a is the specific area, and $C^*_{CO_2}$ and C_{CO_2} are the CO_2 concentration at saturation status and in the culture medium, respectively. The mass transfer coefficient $k_l a$ is a function of microalgal bio-characteristics and operating conditions. Several novel theoretical equations have been developed to model the mass transfer between CO_2 and microalgae, e.g., linking the overall volumetric gas–liquid mass transfer coefficient with the gas holdup and the superficial aeration velocity and other principal operation variables [108], or using a nonequilibrium mathematical model of CO_2 dynamics considering the hydration of dissolved CO_2 to bicarbonate ion (HCO_3^-) as well as the uptake and/or cycling [109], etc.

As a most important parameter characterizing mass transfer, CO_2 removal efficiency was also used to evaluate the microalgal-CO_2 fixation performance in a PBR in addition to the mass transfer

coefficient. It can be determined or calculated by the difference of the CO_2 concentration between the influent and effluent gas of a PBR. Experiments showed that a PBR could reach to higher CO_2 removal efficiency if the high-performance microalgal species were used under optimized operating conditions, e.g., for microalgae *Chlorella* sp. at CO_2 concentrations of 2%, 5%, 10% and 15% (v/v), the CO_2 removal efficiency was 58%, 27%, 20% and 16%, respectively [60]. Other microalgal species, *S. obliquus* WUST4 can adapt to the acural flue gas and reached to the CO_2 removal efficiency of 67% under 12,000–13,000 lx light intensity, 12% CO_2 concentration and 0.1 vvm aeration rate [110].

6. Process improvement and application

Over the past two decades, microalgae-based CO_2 fixation, biomass production and its energy utilization have made great progress in both bench-scale scientific research and pilot-scale application [111–113]. Currently, more than 50 institutions in the world are committing to commercialization of microalgal technology and products. Details of the startup companies are available in Ref. [114–116]. They are distributed in the America (~66%), Europe (~14%), Asia (~16%) and others (~4%). Volumes and sizes of some photobioreactors (PBRs) for laboratory-scale microalgal-CO_2 fixation and biomass production were listed in Table 1. The features (pros and cons) of PBRs for large-scale industrial application were summarized and compared according to their structure and technical–economic performance [117,116,14].

Process improvement as a middle measure is important to ensure microalgal-CO_2 fixation and biomass production more efficiently. Whether bench-scale research or pilot-scale application, performances of carbon fixation and biomass production highly depend on the process conditions and parameters. For the bench-scale research, the selection, cultivation and promotion for high-performance microalgae species may be one of the important goals. Besides, the performance evaluation of microalgae under the harsh process parameters and environmental factors (e.g., high CO_2 concentration, high temperature and toxic pollutants in flue gas) is also needed to be determined by laboratory research. For the pilot-scale application, microalgal cultivation is mainly affected by the culture temperature, light exposure and hydrodynamic conditions. Compared to closed cultivation, open cultivation is more sensitive to and influenced more significantly by these factors, e.g., the outdoor temperature and light intensity variation in day–night and different season have more adversely influence on microalgal growth.

Usually, the open microalgal cultivation includes shallow, mixed and raceway ponds. They have the advantages of extremely simple construction, low-cost operation and easy maintenance. The open ponds are designed as 0.25 m in width and 0.2–0.5 ha in area for commercial microalgae production [118,119]. However, due to the limitation of light penetration they are unable to be designed with large depth, usually 0.15–0.35 m and maximum 0.4 m in depth in order to ensure the light exposure to microalgal cells. Considering the economic effect, the open ponds are usually lined with cement. In some cases, plastic materials were used to enhance light exposure, minimize the effect of temperature fluctuation and prevent microalgae from cross contamination. Moreover, the open pond can be also installed with paddle wheel in practice, which actually could enhance the process parameters such as turbulence mixing and mass transfer.

Another kind of high rate pilot-scale microalgae production is closed cultivation, including cultivation using tubular, bubble column and air-lift, and flat plate PBRs. No matter what kind of design, the improvements of process parameter for CO_2 fixation and biomass production are mainly focused on physicochemical parameters, e.g., light exposure and nutrition conditions, and hydrodynamic parameters including mixing and mass transfer by increasing the gas–liquid contact area and retention time, although there is still controversies in the economy and practicality when they are scaled up for commercial use [120]. Specifically, for the tubular PBRs, the diameter was designed to be about 5 cm for small scale and 10–20 cm for large scale. As expected, decreased diameter and right position (e.g., horizontal or vertical position) help improve the light exposure [121]. For the purpose of high concentration culture, tubular PBRs need to be scaled-up by means of increasing the tube length and diameter. However, increase of length may give rise to the nonuniformity of CO_2 mass transfer and accumulation of dissolved oxygen, and increase of diameter results in an adverse effect on the light characteristics [122]. In comparison, using multiple parallel-tube configurations and increasing the tube unit number without increasing diameter may be more acceptable measures to improve light exposure and mass transfer. Compared with tubular PBRs, PBRs using bubble column design were considered to be competitive in technical-economic performance. Bubble column PBRs can be designed as more than 2–5 m in height and 50 cm in sectional dimension with rounded or rectangular cross-sections. A vertical orientation is helpful to save land area and reduce energy consumption, making it easy to scale-up. Additionally, it has a wide adaptability to light intensity and superficial gas velocity, making it easy to operate. Given the physicochemical parameters, improvement of key operating parameters including appropriate increase of gas hold-up and decrease of bubble diameter, are in favor of enhancing their turbulence and mass transfer performance in gas (CO_2)–liquid (culture medium)–solid (microalgae cell). In practice, bubble columns can also be designed as multistage or series connection to obtain high CO_2 fixation and biomass productivity. As other vertical PBRs, air-lift PBRs are also considered to have an improvement on gas–liquid mixture and light/dark cycle. However, the potential risk in microalgal cell damage due to high shear effect should be avoided. Flat panel was considered as another kind of closed microalgae cultivation system for large scale application. They are usually featured with large surface area and vertically suspended orientation, which effectively increase the surface area illuminated by both direct and diffuse light and provide structural support and even temperature control to optimize microalgal growth [123–125,94]. CO_2 fixation and biomass production can be improved using high aeration rate to accomplish turbulence mixing, CO_2 mass transfer and removal of excess oxygen in the culture medium [105]. However, this configuration still would be challenging due to the high stress to microalgal cell and high operating cost. In addition, some other else special PBRs were also used in practice, e.g., a tower PBR is able to achieve CO_2 fixation and biomass production from combustion flue gas [114]. This structure increases the gas–liquid contact area and retention time using multi-layer design and keeps constant light intensity using a built-in light source.

Overall, microalgae-based CO_2 fixation and biomass production in practice are also influenced by multiple process factors including microalgal species, physicochemical and hydrodynamic conditions as mentioned above. Therefore, to maximize the performance on CO_2 fixation and biomass production, the synergistic effect and global optimization (optimization of PBR design is essentially included in the process parameter optimization) of process parameters are important issues and still required to be solved when using microalgae-based CO_2 fixation and biomass production in the industrial fields.

7. Conclusions and prospects

Recent progresses on process effect of CO_2 fixation and biomass production using microalgae were summarized and reviewed, with

focusing on microalgal species, physicochemical and hydrodynamic process conditions. On the whole, the microalgal-based CO_2 biofixation and biomass production has broad prospects for development. But the following issues still need to be solved in the future.

The selection and cultivation of energy microalgal species: Most of microalgae which are suitable for sequestration of CO_2 from flue gas are the single-cell microalgae especially on *Chlorophyta*. They have high growth rate and strong environmental adaptability, such as good endurance to high CO_2 concentrations, high temperature and low pH value. However, most of them were selected and separated on the basis of bench-scale domestication. They are hardly to be used for pilot-scale cultivation and CO_2 fixation. Therefore, selection and cultivation of the nature microalgae species, which are more suitable for large-scale sequestration of CO_2 from actual combustion flue gas, is still required in the future.

Mechanism of action and interactive influence of multiple process factors: Usually, most of the physicochemical and hydrodynamic process parameters have important nonlinear effects on microalgal growth and its carbon sequestration performance. However, their detailed mechanism of action, especially the impact on the activity of carbonic anhydrase (CA) and regulation and control of CO_2 concentrating mechanism (CCM) have not yet been completely revealed and still need to be explored. Additionally, for microalgal growth and carbon sequestration, it is important to comprehensively consider the effects of all process factors. Previous studies mainly focused on the independent effect of the single factor or interactive effect of two factors (C and N) interactive effect. Up to now there are few investigations involving the comprehensive relationship between microalgal CO_2 fixation/biomass production kinetics and process parameters. The related issues about multi-objective optimization are also rarely reported.

CFD-based PBR design and process conditions optimization: Despite the different photobioreactor geometries and configurations used in open and closed type cultivation, they are essentially similar because they are both used to intensify the mass transfer and the photosynthesis between the microalgal cells and the outside environment. To mathematically model these processes, some new theories and technologies, e.g., CFD model coupled with mass transfer model, chemical reaction and equilibrium model, light attenuation model and new membrane theory, are worth to be further developed to design the photobioreactor geometry and optimize the operating conditions, in order to improve CO_2 fixation and biomass production performance for microalgae.

Resourcelization and energy utilization of microalgal biomass product: It is important to use the microalgal product as biofuel after carbon biofixation due to the situation of global energy crisis. With the development of new efficient and economical conversion technology, microalgal energization including liquid extraction and co-gasification will have a broad developing prospect. It will be helpful to realize the dual objective including both emission reduction of CO_2 and reuse of biomass product.

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